Stealth Plumes on 10.

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Abstract. We suggest that 10's eruptive activity may include a class of previously undetected $S0_2$ geysers. The thermodynamic models for the eruptive plumes discovered by Voyager involve low to moderate entropy $S0_2$ eruptions. The resulting plumes are a mixture of solid and gas which emerge from the vent and follow essentially ballistic trajectories. We show that intrusion of silicate magma into buried $S0_2$ deposits can create the required conditions for high entropy eruptions which proceed entirely in the vapor phase. These purely gaseous plumes would have been invisible to Voyager's instruments. Hence, we call them "stealth" plumes. Such eruptions could explain the "patchy" SO_2 atmosphere inferred from recent UV and microwave sped ral observations. The magma intrusion rate required to support the required gas production for these plumes is a negligible, fraction of estimated global magma intrusion rates.

The most spectacular expressions of 10's volcanic activity are the large, umbrella shaped eruptive plumes discovered in Voyager camera images [*Morabito et al.*, 1 979; *Smith et al.*, 1 979]. These plumes rise to altitudes of' several hundred kilometers, implying ballistic vent velocities of 0.5- 1.0 km s^{-1} [*Smith et al.,* 1979; *Strom et al.*, 1979, 1981_I. At least nine such plumes were observed in eruption by Voyager. Eight of them were apparently active over the. four months separating the two Voyager encounters. There is also abundant evidence in the images for surface deposits formed by similar activity at many other locations [*Smith et al.,* **1979].**

The primary model proposed to explain these features involves phase change, geyser-like eruptions in the low' gravity and low pressore atmosphere of 10. The theoretical basis for this class of eruptive activity was laid by Kieffer [1982]. She explored a wide variety of possible combinations of compositions, reservoirs and vents which could produce the observed characteristics of the plumes. The. most likely fluids for driving 10 plumes nre believed to be $S0_2$, which has been detected as both solid and gas on Io [e.g., *Hanel et* al., 1979; *Pearl et al.*, 1979; *Fanale* ***et al.,*** 1 979; *Smythe* ***et al.,*** 1 979], and sulfur, proposal as both a colorat ion agent on the surface [*Wamsteker* ***et al. , 1974; see*** review by *Nash* ***et al.,*** 1986] and as a possible candidate for lava flows [*Sagan*, 1 979].

Kieffer [1982] organized the discussion of the thermodynamics of such plumes by composition (in this case S or '$S0_2$) and the conditions at the interface between the geyser and its reservoir. The type of plume resulting from each combinat ion can be described in terms of the driving material's phase behavior in a temperature/entropy diagram (Figure 1). Isentropic flow from the initial state in the reservoir (at depth) to 10's surface conditions (80- 130 K, -1-10 nanobar) determines both the mixture of phases and the maximum velocity obtainable at the veot.

On the basis of these models, it has been argued that many of the plumes observed by Voyager can be expliined by low to moderate entropy SO_2 eruptions from reservoirs of liquid $S0_2$ at temperatures consistent with contact with liquid S [*Smith et al., 1979; Kieffer, 1982].* The type example of such a plume is Prometheus. A Prometheus-type plume emerges from the vent as a low temperature (-100 K) mixture of gaseous and solid SO, (Reservoir 11, Figure 1) moving at high velocity (-0.5 - 0.6 km s‘). The resultant eruption is observable by means of light scattered from the $S0_2$ condensates. Pele provides an example of another class of plume. This class has higher eruption velocities, lifetimes shorter than Prometheus-type plumes, and less observable condensates in the core of the plume. Pele-type plumes have been modelled as sulfur energized by contact with silicate magma [*McEwen and Soderblom, 1983],* alt hough high entropy SO_2 eruptions could supply the required high velocity [*Kieffer, 1982].*

We propose that another class of plume may be even more common than those detected by Voyager. This class results from a "high entropy" SO_2 eruption path in which the $S0_2$ is energized by contact with silicate magma. In this case the reservoir (Kieffer's Reservoir V) is characterized as " SO_2 superheated vapor in contact with or degassing from a hypothetical silicate melt at 1.5 km depth. P = 40 bar, T = 1400 K...".

Sulfur dioxide eruptions under these conditions have a number of interesting characteristics. Figure 1 shows the. thermodynamic path followed by a Reservoir V eruption. This class of eruption proceeds entirely in the vapor phase, with a flow of high velocity, cold gas emerging from the vent into the near-vacuum above 10's surface [*Kieffer,* 1982]. High entropy plumes would not have been easily detected by Voyager. The cameras would not have detected molecular scattering from gas unless the abundance was at least several hundred meter amagats, [*Collins, 1980]* far denser than the maximum of -1 0^{-3} meter amagats seen over Loki by the Voyager Infrared Spectrometer (IRIS). The IRIS could only detect SO_2 gas when a large hot source on the surface was under a plume. Loki was the only such observed coincidence [*Hanel et al.,* 1979; *Pearl et 01.*, 1979; *Pearl and Sinton, 1982].* Thus, high entropy plumes would generally be invisible. Hence our term "stealth" plume.

Kieffer's Reservoir V is a physically reasonable case for a silicate magma intrusion srt depth into a body of liquid SO_2. Initial temperatures and pressures leading to even higher entropy for the initial reservoir would also lead to "stealth" characteristics. Intermediate, lower temperature, lower entropy cases (between the paths for Reservoirs IV and V in Figure 1) could lead to nearly "stealthy" plumes with low frictions of condensed SO_2, depending on the actual pressures at the vent. It is possible that some "transparent" Voyager plumes with no obvious opt ically thick eruption columns - like Pelt - are examples of such nearly "stealthy" behavior. We will consider the characteristics of Reservoir V eruptions for the rest of this paper as being the type example for pore gas phase eruptions.

Both SO_2 find silicate magmas are needed at depth to crest e Kieffer's Reservoir V. More evidence for silicate magma activity has become available since Kieffer's original work. Infrared observations of 10 over the last decade have detected short lived hotspots with temperatures indicative of silicate lava (> -1000 K). Analysis of these events, and other characteristics of the thermal anomalies on 10, suggest that silicate volcanism may be responsible for most of the hotspot and resurfacing net ivity [*Johnson et* al., 1988; ***Veeder et al.*, 1994; *Blaney et al.*,** 1995].

We expect that volcanic activity on 10 is capable of producing the conditions needed to create the required $S0_2$ subsurface reservoirs. The observed plumes indicate that these deposits are indeed present at depth. To investigate how these volatile deposits could be buried by lava flows requires modelling the heat transfer from a solidifying, and cooling silicate body to a melting and vaporizing volatile component. In general, this is a complex problem. However, large scale volcano-groundwater interactions of this type have been considered for Mars [*Squyres et al.*, 1987]. They modelled the mobilization of water, making up 25 % volume of a permafrost layer, by flows and sills. This process is analogous to what may be happening on Io with SO_2. We use the results of Squyres *et al.* to estimate the volumes and rate of $S0_2$ mobilization.

We consider the differences between the Mart irm and Ionian environments (surface t emperature, thermal gradient), and between wrtter and SO_2 as the major volatile (specific heat capacities, latent heats of solidification and vaporization, melting and vaporization temperatures). Generally, a silicate flow on the surface of 10 is capable of mobilizing a column depth of SO_2 (liquid and gas) roughly equivalent to the thickness of the flow. Most of the heat in the flow is lost from its upper surface by radiat ive transfer. Surface flows mobilize an average of shoot 2 x 10'6 m see", per unit area of the flow, of SO_2 during the first five days after emplacement. This drops by rtn Order of magnitude over the next 50 days. Each subsequent lava flow will mobilize less SO_2 than its predecessor, provid ing a mechanism for capping and burying the deposit. Later intrusion of silicates into the reservoir would easily create the required Reservoir V condit ions.

It is entirely possible that these purely gaseous eruptions rtre more common than the visible plumes seen by Voyager. We suggest that such plumes may help explain recent observations of SO_2 gas on 10 using UV and microwave sped roscopy [*Lellouch et al., 1992; Ballester et al.*, J 994]. These authors suggest that SO_2 is distributed in a "patchy" manner covering 5-20 % of the surface, with 1OCSSI column densities of about 10'7 cm^{-2} (as opposed to a uniform atmospheric layer). Furthermore, Lellouch *et al.,* [1 994] suggest that the observed microwave spectral characteristics might be produced by cold gas in many ballistic plumes.

However, at the time of Voyager, Prometheus-type plumes covered less than 1 % of the Ionian surface area [after *Strom and* Schneider, 1982] .

It is possible that the general level of plume activity is greater in recent years than in 1979. However, several lines of evidence suggest that activity on 10 has been relatively stable for decades. Optical observations snow little or no change in its brightness, color or rotational variation since 1928 [*Morrison et al.,* 1979] and recent HST observat ions show an UV albedo pattern (believed to be related to SO_2 deposits) very similar to that seen by Voyager [*Sartoretti et d., 1994].* Oor infrared data also indicate relatively constant heat flow over the last decade [*Veeder et al.,* 1994]. We propose instead that unseen "stealth" plumes are a permanent feature of 10's volcanic activity and are respon- sible for the additional $S0_2$ detected by Lellouch et *al.*

Is the amount of power required to create and sustain stealth plumes on 10 reasonable? We can estimate the amount of heat t ransport necessary to keep soch a global geyser system running. The first step is to calculate the power necessary to produce 10's atmosphere by vaporization of SO_2 • We assume 1 O% surface coverage with a local column density of 1017 cm^{-2}. This is 4 x 10'3 $S0_2$ molecules, or 4.4 x 10^8 kg of $S0_2$. The amount of heat energy required to convert this quant ity of $S0_2$ liquid to vapor is 1.7 x 101' J (assuming heat of vaporizat ion of 3.89 x 1@ J kg^{-1}). To supply this amount of heat requires the solidifying and cooling of 8 x 10^6 kg of silicate magma (heat of fusion ≈ 4 x 10^5 J kg^{-1}; specific heat capacity ≈ 1500 J kg^{-1} K"]) from its liquidus temperature (1 475 K) to 300 K. The volume of magma required to volatilize the $S0_2$ molecules seen over the surface At any given time IS - 3 x 10^3 m^3. Since the ballistic time scale in a typical plume is -1 0^3 s [*Johnson and Soderblom, 1 979]* the SO_2 discharge rate required to sustain the observed gas is 4.4 x 10^5 kg s^{-1}. This can be sustained by the heat content of 3 m^3 s^{-1} of silicate magma. This is a trivial rate when compared with the estimated global silicate extrusion rate of 1.7 x 104 m^3 s")from Blaney *et al.*, [1995]. We have no direct evidence for the int rusive rate on 10. However, rates of extrosive and intrusive activity are of the same order of magnitude in systems studied on Earth. For example, the ratio of extrusive to intrusive terrestrial basaltic volcanism is about 1:3 [e.g., *Dzurisin et al., 1984].* If this ratio also applies to Io, then the subsurface intrusion rate on 10 is -5 x 104 m^3 s^{-1} of which only -0.001 % is required to be available for vapor- izing SO_2. Thus we believe there are abundant sources of silicate magma to power the inferred plume activity, both seen and unseen.

Voyager may in fact have seen evidence for stealth plume activity. A long exposure image of Io's nightside detected several localized regions of auroral emissions [*Cook et* al., 1981]. Several of these areas were correlated with known phone locat ions, but some were not and might have resulted from gas in otherwise undetected plumes. In addition, numerous circular albedo features similar to plume deposits were seen in areas not dissociated with an "active" plume (e. g., Surt in Voyager 2 images). These refly be either relics of past eruptions or, perhaps, deposits from stealth plumes condensing on the surface. Stealth plumes mrry also have affected the Pioneer 10 radio occultations. Johnson and Matson [1989] noted that 10's ionosphere inferred from the exit profile of Pioneer 1 O's radio occultation was essentially above the most prominent and long lived active volcanic feature on 10 - Loki Patera. The entry profile, however, is not associated with any known Voyager plume. If there rrrc in fact more clear (rind therefore unseen) gas plumes than visible plumes (as seen by Voyager), it seems likely that rrny spacecraft occultation has a good chance of sampling a " locally" derived atmosphere. Galileo, with several planned rrrdio occultations, hrrs an opportunity to better determine the distribution of both Voyager-style and "stealth" plume activity on Io.

We predict that Galileo should be able to detect the effects of stealth plumes in one or more of the following ways: (1) ionospheric measurements from radio occultations; (2) localised auroral phenomena, and (3) localised albedo changes.

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Figure 1. Temperature-entropy phase diagram of SO,. Heavy solid lines are phase boundaries; heavy dashed or dotted lines are extrapolated beyond data sources; thin lines are isobars. Specific enthalpies are shown in parentheses. Isentropes I-V (shown with the thin arrows) are examples of volcanism at both high and low entropy. Isentrope V is the “stealth plume" path discussed in the paper [from *Kieffer*, 1982].

Figure 1. Temperature-entropy phase diagram of SO_2. Heavy solid lines are phase boundaries; heavy dashed or dotted lines are extrapolated beyond data sources; thin lines are isobars. Specific enthalpies are shown in parentheses. Isentropes I-V (shown with the thin arrows) are examples of volcanism at both high and low entropy. Isentrope V is the “stealth plume” path discussed in the paper [from *Kieffer*, 1982].

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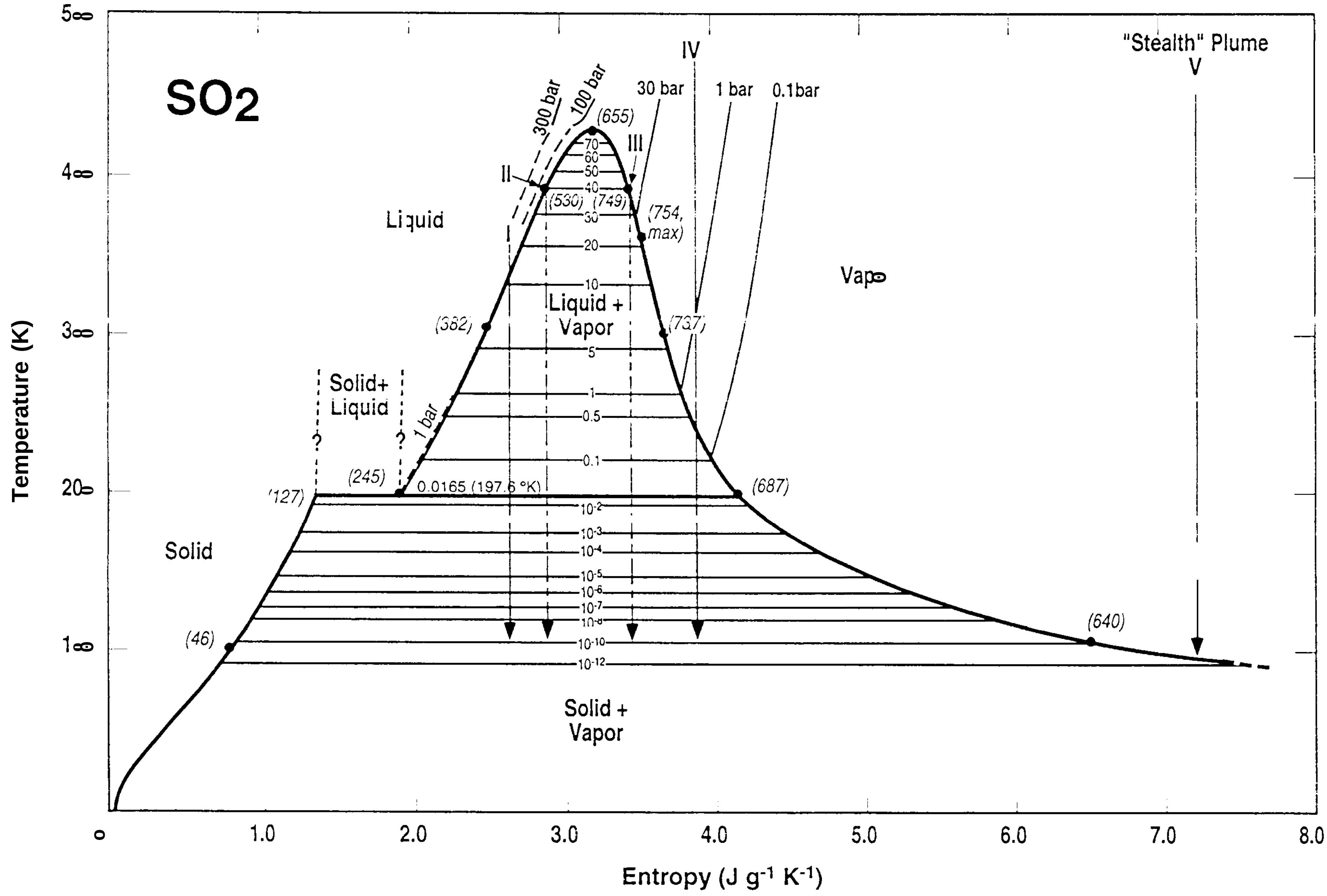

SO2
Liquid
Solid+ Liquid
Solid
Liquid + Vapor
Solid + Vapor
Vapor
300 bar
100 bar
30 bar
1 bar
0.1bar
IV
II
III
"Stealth" Plume V
(655)
(530)
(749)
(754, max)
(382)
(737)
(245)
(127)
(687)
(46)
(640)
0.0165 (197.6 °K)
70
60
50
40
30
20
10
5
1
0.5
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-10}
10^{-12}
?
?
Temperature (K)
Entropy (J g^{-1} K^{-1})
0
100
200
300
400
500
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0